High Temperature Electronics for Atmospheric Probes and Venus Landed Missions

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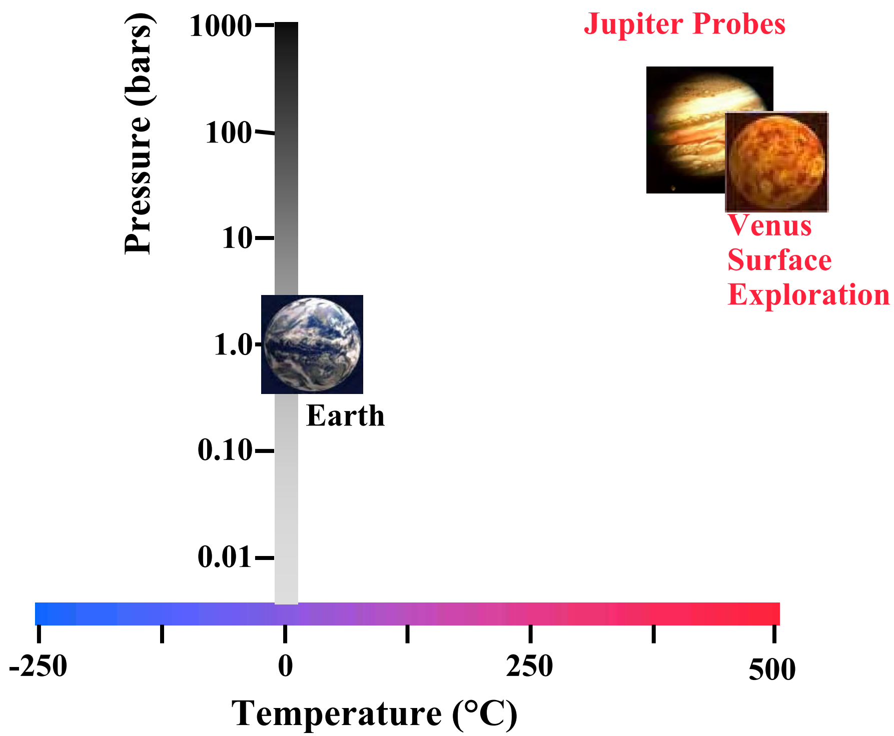
High Temperature Space Environments



Mission Category	High Temp (°C)	Pressure (bar)	Other Environmental Conditions
Venus Surface Exploration and Sample Return	+480	92	Sulfuric acid clouds at 50 km; 97% CO_2, acids residues at the surface
Giant Planets Deep Probes	+350 to 450	50-100	

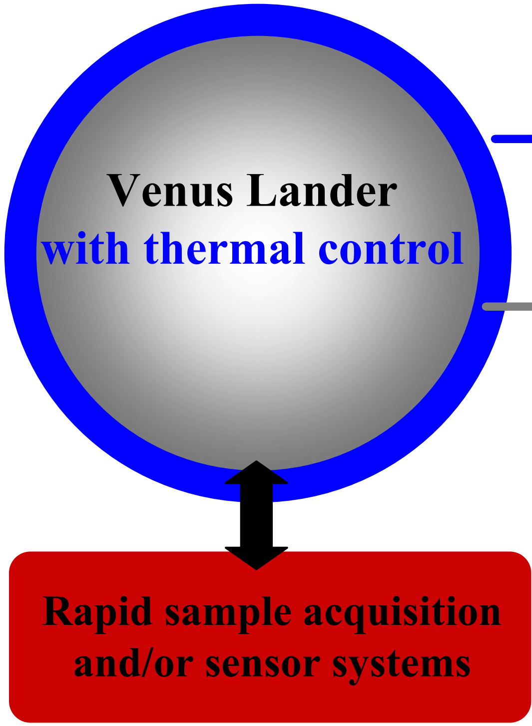
Past Missions in High Temperature Environments: Landers, Balloons, and Probes

Surface Landed Missions	Launch	Surface Survival Time (min)	Pressure Vessel	Thermal Control	HT Sample Acquis.
Venera 7	1970	23	No	No	No
Venera 8	1972	50	Yes	Yes	No
Venera 9	1975	53	Yes	Yes	No
Venera 10	1975	65	Yes	Yes	No
Venera 11	1978	95	Yes	PCM	No
Venera 12	1978	110	Yes	PCM	No
Pioneer Venus	1978	60	Yes	No	No
Venera 13	1981	127	Yes	PCM	Yes
Venera 14	1981	57	Yes	PCM	Yes
Vega Lander	1984		Yes	PCM	Yes
Balloon/Probe Missions		Survival Time (min)			
Vega 1 Balloon	1984	47 hrs at 54 km	Yes	PCM	No
Galileo Atmospheric Entry Probe	1995	58 min, 150 km into Jupiter atmosphere	No	Yes	No

*PCM-Phase Change Materials

- In all successful Venus landings, the maximum survival time on the surface was 2 hours.
- No extended surface missions (> 10 hours) was attempted.
- No high temperature batteries or high temperature electronics were used.

System Requirements



~480°C

Key High Temperature Components:

- Pressure vessel integrated with advanced thermal control
- High temperature electronics
  - Low power, operating at ~300°C
  - Some components (sensor and actuator interfaces and/or telecomm) at 480˚C
- Rapid data acquisition system
  - Rapid sample acquisition system at 480˚C
  - Rapid sample processing and analysis
- High temperature energy storage

Jupiter atmospheric probes:

- Advanced pressure/temperature control:
  - Alternative pressure vessel materials and design
  - Advanced, lightweight passive thermal control
- High data rate/penetration telecommunication technology

Technology Need

	Venus In-Situ Exploration				Atmospheric Probes	
Technology	**Short-Lived Surface Mission (full science suite)**	**Long-Lived Surface Mission (focused science) small sensor/sample acquisition systems at ambient**	**Extended Surface Mission (full science suite)**	**Sample Return**	**SoA (Jupiter) Probe (20 bar)**	**Deep Probe (100 bar)**
HT Electronics	Low	Very High	Very High	Low	Low	Med
HT Communication System	Low	Very High	Very High	Low	Med	High
HT Sample Acquisition	Very High	Very High	Very High	Very High	Low	Very High
HT Energy Storage	Low	Very High	Very High	Very High	Low	Med
Pressure Vessel	Med	-	Very High	Med	Med	Very High
Passive Thermal Control	Very High	-	Low	Very High	Med	Very High
Active Refrigeration	Low	-	Very High		-	-

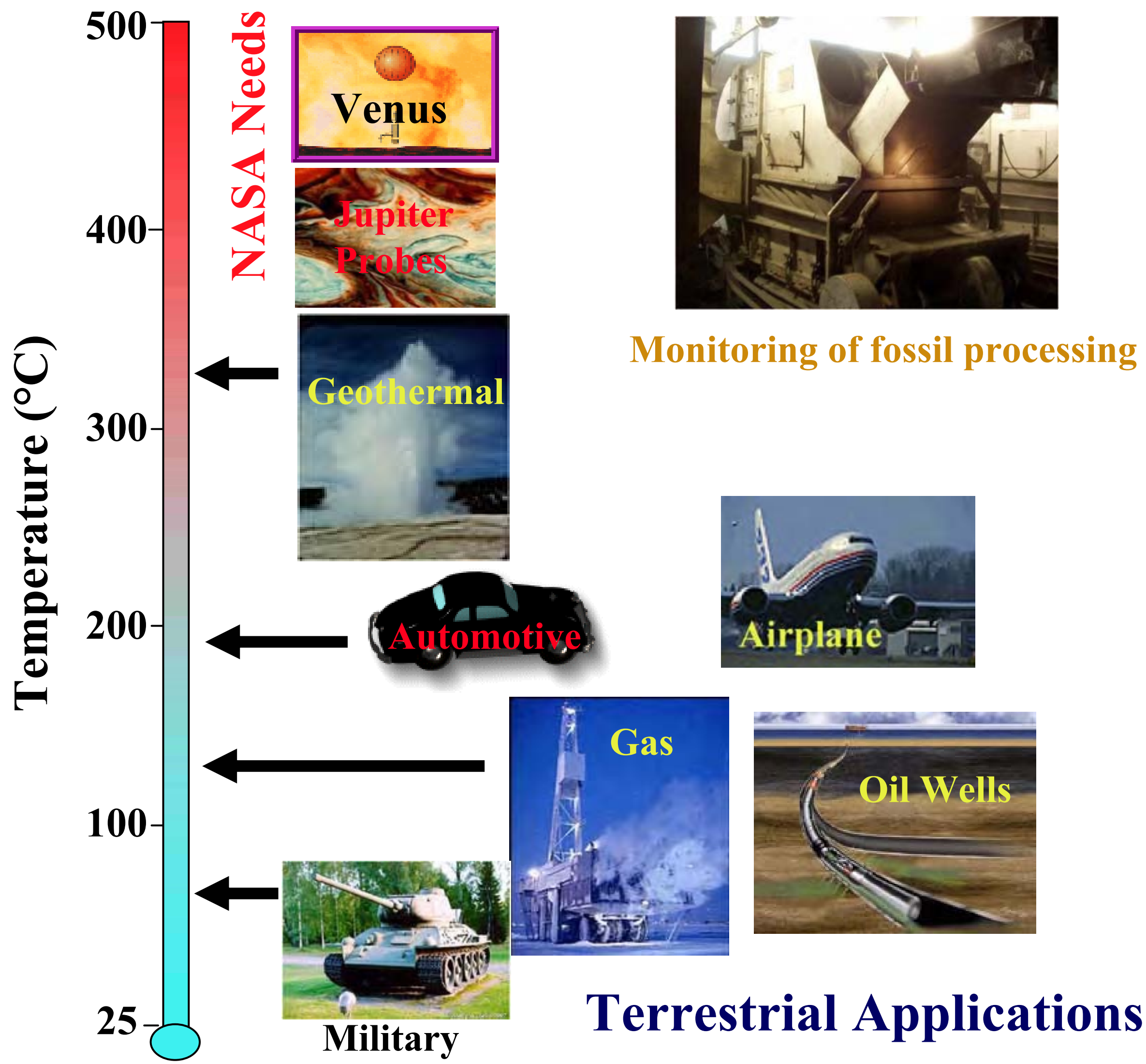
Issues for High Temperature Electronic Systems

- System Requirements:
  – Conditions under which electronics are expected to operate.
- Survivability:
  – Maximum operating temperature of active devices, passive devices, and packaging materials cannot be exceeded.
- Lifetime:
  – Due to issues such as diffusion, oxidation, and chemical reactions, devices will degrade with time and temperature.
  – Such degradation must be understood and taken into account when designing system.
- Level of functionality:
  – Electronics capable of functioning at the higher desired operating temperatures (+480°C) do not possess the level of complexity available with standard Si electronics that operate within the standard commercial (0 to +70°C) or Mil Spec (-55 to +125°C) temperature ranges.
- Reliability and Repeatability
- Cost

Non-NASA Applications

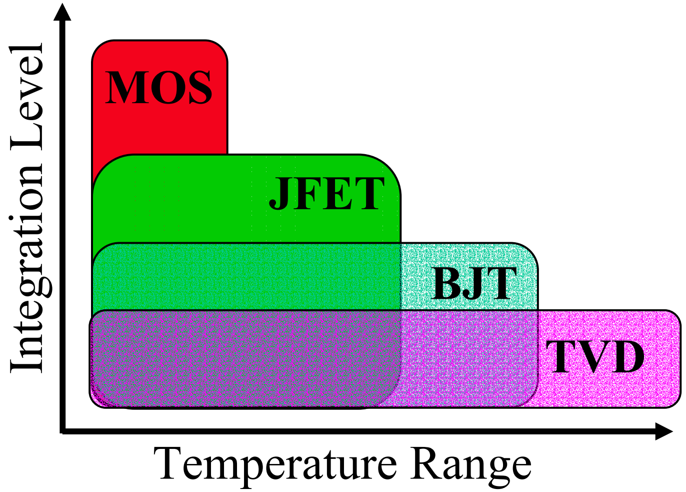
Synergy:

- Department of Energy – fossil processing plants
- Geothermal and oil drilling
- Automotive and aerospace industry
- Military



Active Devices-Solid State

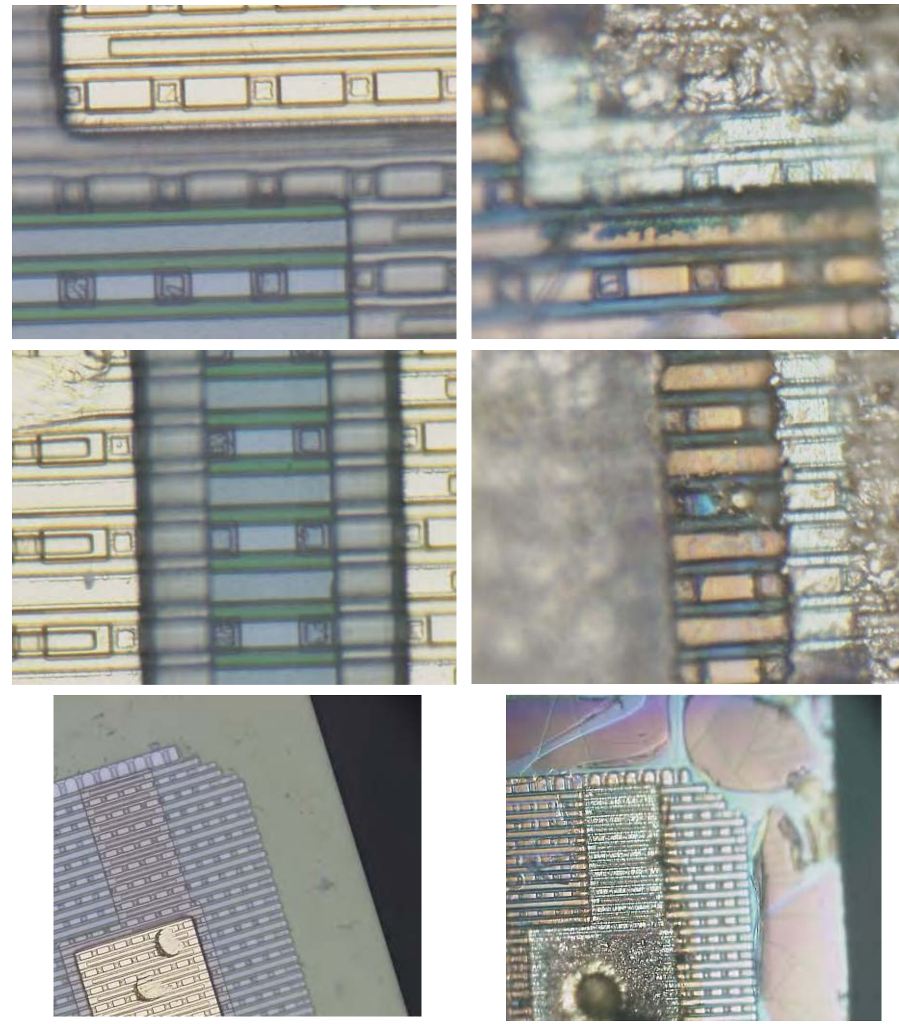
- Silicon on Insulator (SOI) Devices:
  - Due to significant increase in leakage current at higher operating temperatures, Si bulk devices can be effectively used up to 200°C.
  - For functionality up to 300°C, leakage current may be managed using SOI technology. Large feature sizes and non-conventional metallizations will increase devices lifetime.
  - SOI technology is currently used in oil drilling/geothermal wells monitoring equipment.
  - Low power, SOI-based electronics operating at 300°C, can be considered for use within the thermally controlled Venus Lander for atmospheric probes. Such electronics would help to relieve thermal control load and significantly contribute to mission survivability and lifetime.
- Wide Bandgap Devices:
  - For electronics that need to operate above 300°C, wide bandgap semiconductors have to be considered.
  - SiC technology is currently the most promising candidate.
  - SiC devices and primitive circuits have been demonstrated to operate ~ 500°C for limited periods of time (tens of hours).



Material or Device	Max operating temp. (°C)
Bulk Silicon	~225
Silicon on Insulator (SOI)	~300
Gallium Arsenide	~400
Gallium Nitride	~600
Silicon Carbide	~600
Diamond	~1000
Thermionic Vacuum Devices	~900

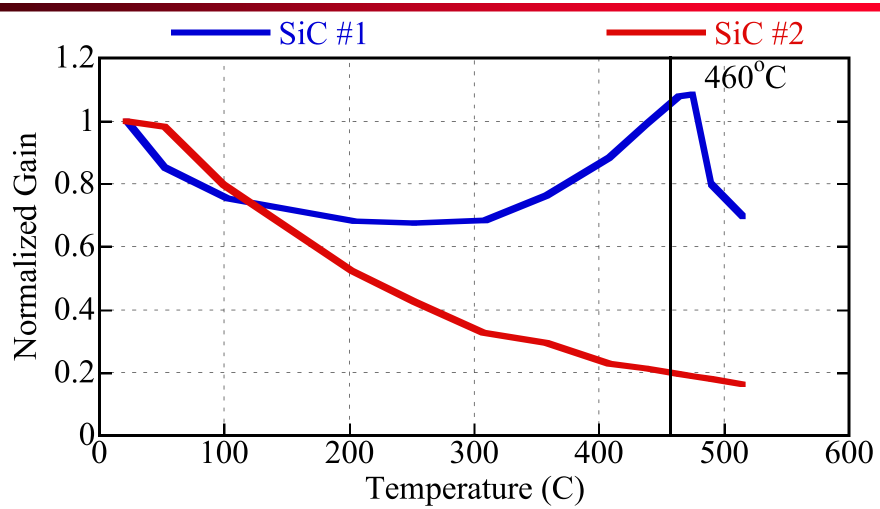
Active Devices-Solid State

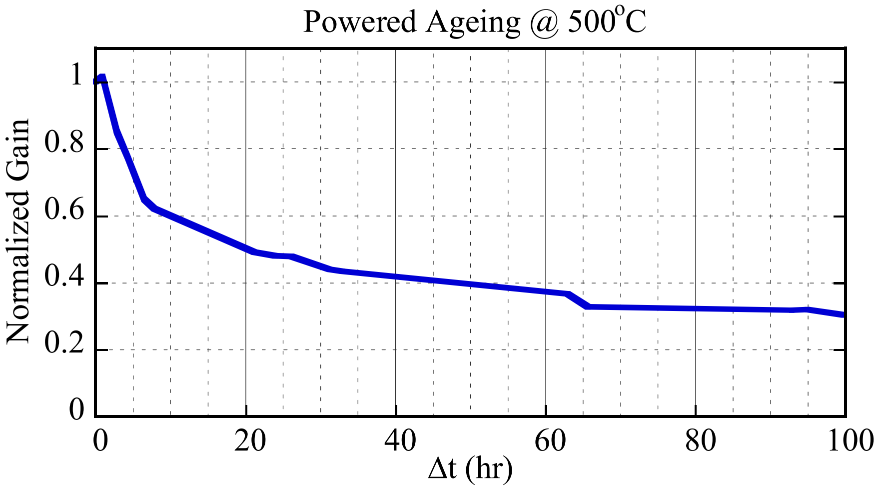
- SiC Devices:
  - Although the theoretical maximum for SiC operation is 600°C, problems with diffusion and oxidation of metal contact layers significantly reduce both operation temperature and lifetime.
  - Primary challenges with this technology include:
    - selection of metal layers to reduce diffusion and oxidation problems,
    - repeatability of SiC growth and metallization processes,
    - integration.
  - Commercially available devices include junction field effect transistors (JFET)s, metal-semiconductor field effect transistors (MESFETs) and bipolar junction transistors (BJT)s. Their development is predominantly focused on applications in high power electronics.



Before **After (500 C/~24 hrs)**

Active Devices-Solid State

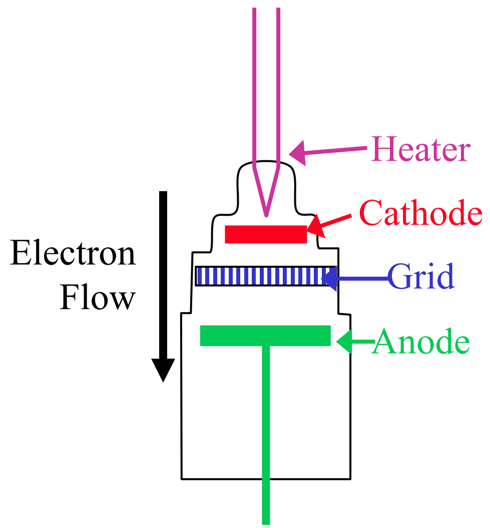


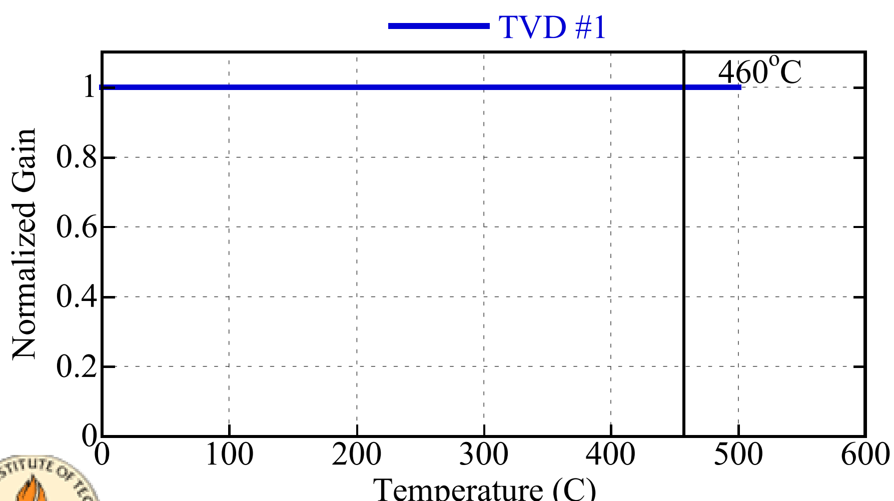


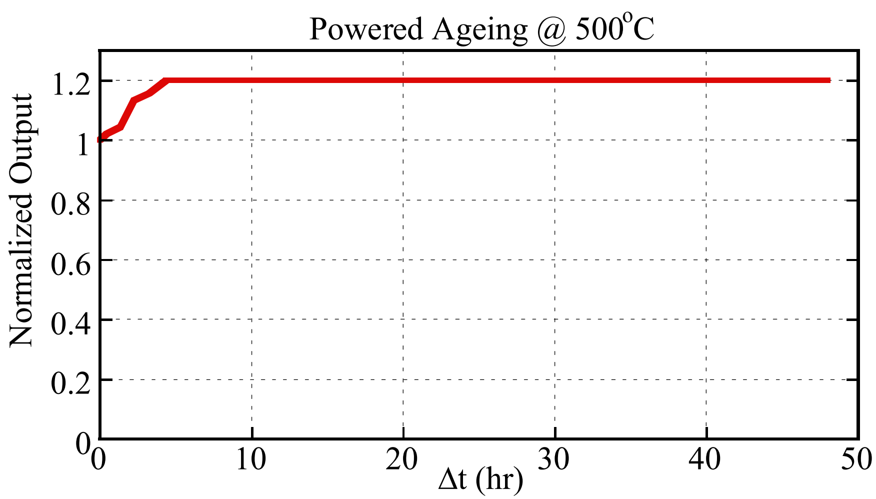
- Influence of temperature:
  - Currently available transistors were not designed for use at these temperatures and are not expected to survive long-term exposure.
  - Selection of a proper metal stack that minimizes diffusion is required to ensure long term survival of SiC active devices-ongoing problem for last 20 years.
  - Integration/Complexity:
    - Since most of the applications of high temperature electronics will involve transmitters for telecom systems, basic operational preamplifiers for sensors and actuators interface, the lack of integrated circuits is not a limiting factor in using SiC in Venus missions.

Active Devices-Thermionic

- Thermionic Vacuum Devices (TVD):
  - TVDs are inherently high temperature devices, because the cathode is designed to run at 700 to 900°C.
  - These devices have been demonstrated for operation within a 500°C environment but must still be optimized.
  - Challenges for the development of this technology include
    - packaging requirements to maintain vacuum at high temperatures and high pressures,
    - issues related to higher levels of integration, and
    - power requirements.

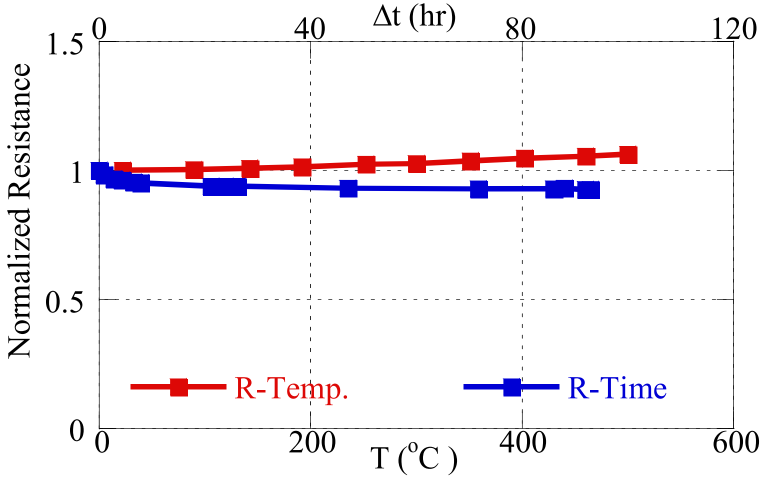






Passive Devices-Resistors

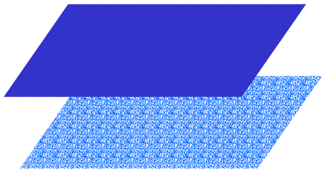
- Elevated temperature concerns include:
  - Noise
  - Thermal stress
  - Interdiffusion
  - Oxidation.
- Thin and thick film resistors deposited on ceramic substrates eliminate the need for mechanical attachment to substrates and the associated failure mechanisms.



	Max T (°C)	TCR	
Thin-film			
Tantalum	> 400	± 100	Needs passivation.
Tantalum Nitride	> 400	- 85	
Thick-film			
Ruthenium-Silver	~ 1000	± 200	Useable to 1000°C.
Ruthenium Oxide	> 1000	100	Superior stability, low TCR, and low noise.

Passive Devices-Capacitors

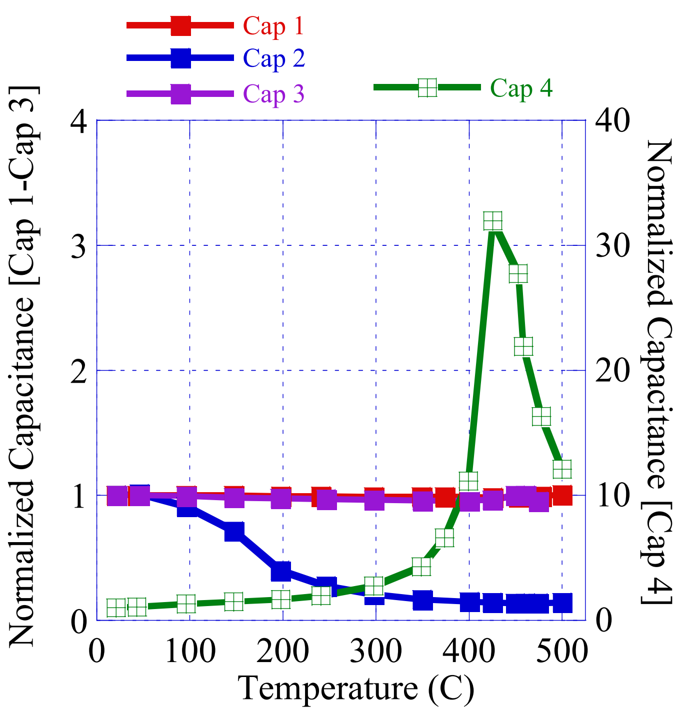
- Capacitors are particularly challenging components to develop for reliable elevated temperature operation.
- Important parameters include capacitance, dissipation factor, leakage current, equivalent series resistance (ESR), voltage rating, dielectric absorption, and volumetric or weight efficiency.

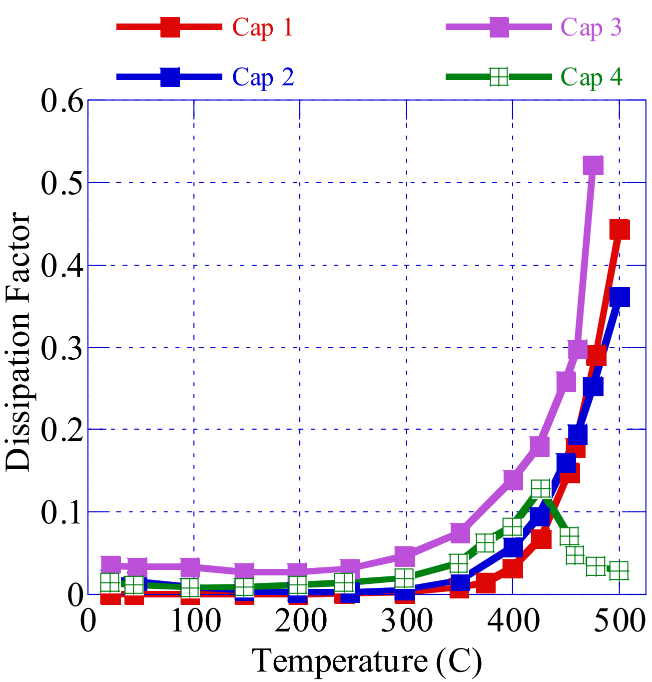


Capacitor	**Max. T (°C)**	**Comments**
X7R	≤ 500	Capacitance is a strong function of temperature. High leakage current at elevated temperatures.
NP0	≤ 500	NP0 is stable up to 500°C with zero coefficient of capacitance. Dissipation problem at high temperatures.
Piezoelectric	Design Dependent	Composition selected to peak in capacitance and dissipation factor for specified temperatures. Difficult to implement.
Diamond	>500?	Theoretically useful to well over 500°C with stable, high capacitance. Still under development to attain uniform diamond film and stable metal contacts.
Air Gap/ Parallel Plate	> 500	Low capacitance, but stable over entire range of temperature. Very large area capacitors would be required.

Passive Devices-Capacitors

- Large-value (several microfarads and higher), low dissipation capacitors for power applications are still in the development phase. Innovations on all fronts, including materials, device designs, and packaging are being pursued.

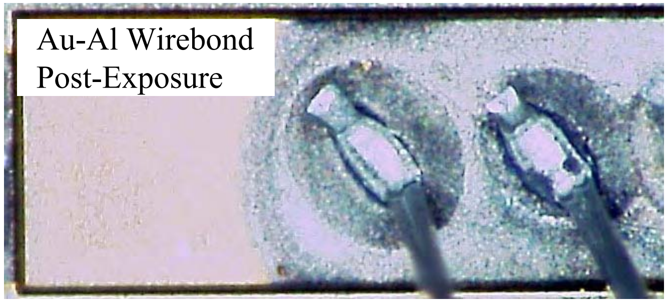


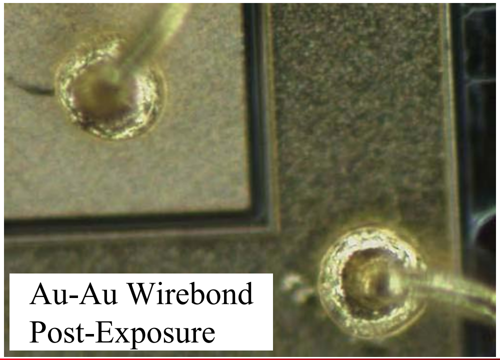


Packaging Materials–Interconnect

- Electrical Interconnect:
  - The primary concern with the selection of interconnect material combinations involves interdiffusion of the pad and wire metals.
  - The formation of brittle intermetallic phases and voids, due to diffusion at higher temperatures, reduce strength and conductivity.
  - Such problems can be minimized through the use of a mono-metallic interface.

Metals: Pad-Wire	**Max. Temp. (°C)**	**Properties/Comments**
Al-Au	175	Forms brittle intermetallic phases which reduce bond strength and conductivity
Ni-Al	300	Interdiffusion creates excessive voids that decrease bond area and strength.
Al-Al	660	Melting temperature of Al.
Au-Au	> 660 (up to 1064)	Melting temperature of Au.

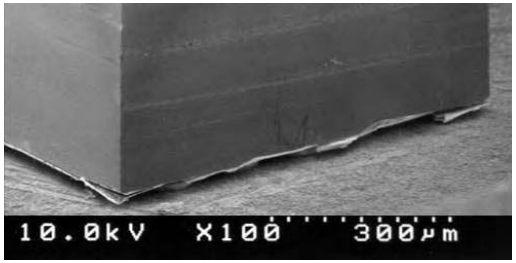

Au-Al Wirebond Post-Exposure


Au-Au Wirebond Post-Exposure

Packaging Materials-Die Attach

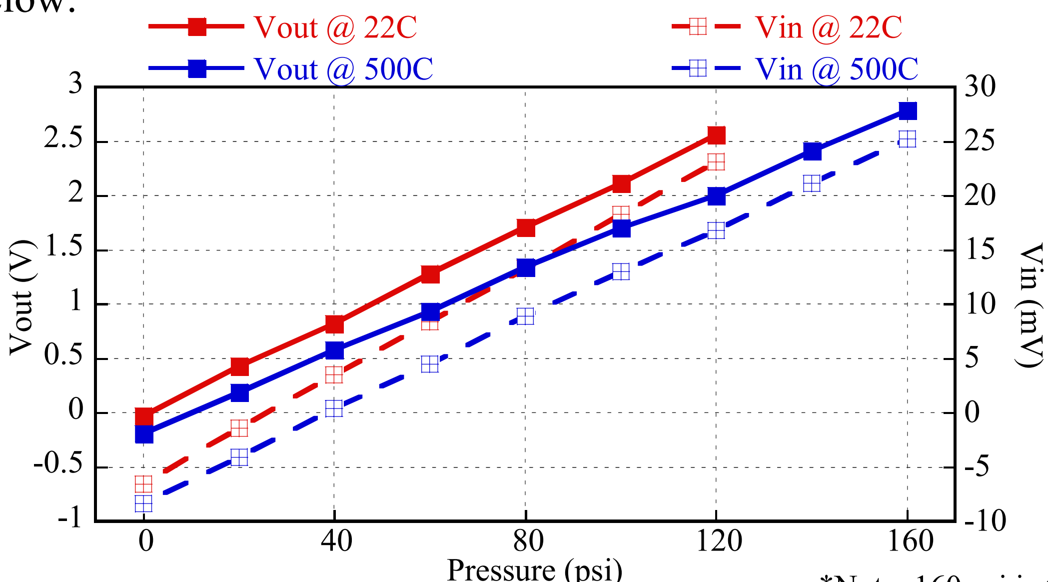
Die Attach Material	Suggested Max. Use Temp (°C)	Limiting Properties/Comments
Solders		
Au80Sn20	280	Eutectic melting point
Au88Ge12	356	Eutectic melting point
Au97Si3	363	Eutectic melting point
Sn5Pb95	308	Solidus
Pb92In5Ag3	300	Solidus
Brazes		
82Au/18In	451	Solidus
45Ag/38Au/17Ge	525	Eutectic
72Ag/28Cu	780	Eutectic
82Au/18Ni	950	Eutectic
Other		
Au thick film paste	> 600	High firing temperature
Au thermocompression bonding	➢500	Assumes Au to Au interface

- Attachment Materials:
  - The function of a die attach material is to secure a die to the substrate, to ensure electrical connectivity to the backside of the die, and to ensure that the die does not fracture following power and temperature cycles.
  - Stiff die attach materials concentrate thermal stresses in the die, which can cause die fracture and fatigue.
  - Peeling stresses at the edge of the die can cause horizontal crack propagation and die lifting.



Pressure Sensor Pre-amplifier

- A high temperature piezoresistive pressure transducer was used to evaluate the functionality of the 460°C pre-amplifier.
- Two pre-amplifier circuits are under development using the components that are most likely to function for extended periods of time at 460°C :
  - Solid State SiC
  - Thermionic Vacuum Device
- The thermionic vacuum device pre-amplifier was evaluated at room temperature and 500°C; preliminary results are shown below.



*Note: 160 psi is the limit of the current test setup.

Summary

- High temperature electronics can play a key role in Venus missions and deep atmospheric probes.
- During last ten years a significant progress has been achieved in both high temperature active devices and electronic packaging.
- NASA needs for electronics are unique; they exceed temperature ranges required for most terrestrial applications.